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Modeling multimodal transportation network emergency evacuation considering evacuees' cooperative behavior

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Abstract

Modeling emergency evacuation could help reduce losses and damages from disasters. In this paper, based on the system optimum principle, we develop a multimodal evacuation model that considers multiple transportation modes and their interactions, and captures the proper traffic dynamics including the congestion effects, the cooperative behaviour of evacuees, and the capacities of the transportation system and the shelters. We further develop a Method of Successive Average (MSA)-based sequential optimization algorithm for large-scale evacuations. Both the proposed model and the solution algorithm are tested and validated through a set of numerical tests on a small network, and a detailed case study on the Lower Manhattan network. The results of the paper can provide insight on modeling flow interactions of different transportation modes and useful guidance on developing evacuation strategies to reduce the system evacuation time and losses from disasters.

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Keywords: Emergency evacuation; multimodal emergency evacuation modeling; interactions of intermodal travels; cooperative travel behavior; MSA-based sequential optimization; large-scale evacuation; double queue model; point queue model; dynamic system optimum.

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1. Introduction

Disasters, either man-made (such as terrorist attacks and chemical leakages) or natural disasters (such as earthquakes, floods, and hurricanes), could result in devastating losses of lives and properties. According to Swiss Re (2016), there were 155 man-made disasters and 198 natural catastrophes in 2015, leaving about 26,000 fatalities and a total economic loss of USD 92 billion. Modeling emergency evacuation, the immediate and urgent movements of people and their properties from disaster-impacted areas to safe ones, can provide guidance on how to reduce the system evacuation time (SET) and mitigate the consequences of disasters by identifying the network operational capacities, bottleneck locations, and the utilization of the transit system, and obtaining the minimum time needed for evacuations (Abdelgawad et al., 2010; Yuan and Puchalsky, 2014).

Numerous emergency evacuation models have been developed in the past; an in-depth review can be found in Murray-Tuite and Wolshon (2013). Several issues are evident in those models. First, those models vary in the assumptions made on evacuees' choices of whether to evacuate or not (Murray-Tuite and Wolshon, 2013), the departure times (US Army Corps of Engineers,1999; Lindell 2008; Pel et al., 2012), the evacuation modes (Renne et al. 2009; Miller et al. 2008; Murray-Tuite and Wolshon, 2013; Yuan and Puchalsky, 2014), the evacuation destinations (Chen, 2004; Cheng and Wilmot, 2009), and the evacuation routes (Pel et al., 2012). With the prevalence of advanced social media (such as Facebook, Twitter, among others), and emerging connected and automated vehicles, drivers will be more and more connected and cooperative. This will enable evacuation planners and operators to dynamically guide the evacuation (e.g., by possibly influencing the evacuees' travel choice behavior) for the benefit of the entire system, e.g., based on the dynamic system optimum (DSO) principle. In this paper we propose modeling evacuations considering the evacuees' cooperative behavior, which, to be specific, refers to the full cooperation among all evacuees, and between the evacuees and the evacuation management agencies and the infrastructure in order to achieve the desirable system optimum. We note that how to achieve such full cooperation is not trivial, which needs to be investigated in future study. However, as shown before (e.g., Ziliaskopoulos, 2000; Liu et al., 2006), the DSO based evacuation modeling methods can indeed provide useful insights on evacuation planning and strategies. Second, the microscopic and mesoscopic models often use predefined parameters which are hard to validate, and meanwhile produce computational challenges for large-scale evacuation problems (Murray-Tuite and Wolshon, 2013). On the other hand, most macroscopic models cannot capture real traffic dynamics such as queue spillbacks. Though the cell transmission model (CTM) has the capability of capturing queue spillbacks, leading to its wide applications in emergency evacuation (Ziliaskopoulos, 2000; Chiu et al., 2007; Liu et al., 2006), it has to decompose the problem over time and space, creating computational difficulties for large-scale evacuation problems (Zheng and Chiu, 2011). Recently, a macroscopic evacuation model was developed based on the double queue concept (Osorio,et al.,2011; Osorio, 2015), which could capture queue spillbacks while at the same time was much easier to compute (Ma et al., 2014a). The model was later applied for modeling the flooding evacuation caused by Hurricane Irene in Troy, NY in 2011 (Ma et al., 2014b). However, so far only autos were considered as the only transportation mode. In practice, it is essential to efficiently utilize the mass transit (including bus, subway, etc.) as an important means to reduce the SET and losses (Renne et al., 2008, 2009; Yuan and Puchalsky, 2014; Hossam et al., 2010).

In this research, we aim to develop a macroscopic multimodal transportation network emergency evacuation model, which considers different transportation modes and their interactions, the proper traffic dynamics (including the congestion effects of autos, buses, and subway trains), the evacuees' cooperative behavior, and the capacities of the transportation system (including roadways, buses, and subway trains) and the shelters based on the DSO principle. Its objective is to minimize the SET including the total travel time on the networks and the total waiting time at origins, bus stops, and subway stations of all evacuees. The constraints are formulated on the intermodal interactions, system traffic dynamics, the initial conditions, flow conservations, and boundary conditions. To capture the interactions among different modes, we model evacuees' dynamics and interactions among different modes at the origins, transferring points (e.g., bus stops or train stations), and shelters. We first apply the *point queue* model to describe the dynamics of "person queues" formed by the evacuees at bus stops and subway stations. Intermodal travel is then captured through modeling the interactions of the person queues with different modes; see Section 2.2 for more details. We then apply the *double queue* model to describe the system dynamics of all the vehicle-based flows (e.g., the auto-based flow and the bus-based flow). The interactions of person queues and vehicle queues are